GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: July 26, 1977

Project Title: High Capacity Laser Holographic Data Storage

Project No: E-21-609

Project Director: Dr. Thomas K. Gaylord

Sponsor: National Science Foundation

Agreement Period: From 6/1/77 Until 11/30/79 (Grant Period)
(24-month budget period plus 6-month flexibility period)

Type Agreement: Grant No. ENG76-81707

Amount: $75,600 NSF
16,798 GIT (E-21-311)
$92,398

Reports Required: Annual Technical Letter; Final Technical Report; Summary of Completed Project

Sponsor Contact Person (s):

Technical Matters

Dr. Elias Schutzman
Engineering Division
National Science Foundation
Washington, D. C. 20550
(202) 632-5881

Contractual Matters
(thru OCA)

Ms. Mary Frances O'Connell
Grants Specialist, Area 4
National Science Foundation
Washington, D. C. 20550
(202) 632-2858

Defense Priority Rating: N/A

Assigned to: Electrical Engineering (School/Laboratory)

COPIES TO:

- Project Director
- Division Chief (EES)
- School/Laboratory Director
- Dean/Director—EES
- Accounting Office
- Procurement Office
- Security Coordinator (OCA)
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- Library, Technical Reports Section
- Office of Computing Services
- Director, Physical Plant
- EES Information Office
- Project File (OCA)
- Project Code (GTRI)
- Other

CA-3 (3/76)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: June 26, 1980

Project Title: High Capacity Laser Holographic Data Storage

Project No: E-21-609

Project Director: Dr. Thomas K. Gaylord

Sponsor: National Science Foundation

Effective Termination Date: November 30, 1979

Clearance of Accounting Charges: --

Grant/Contract Closeout Actions Remaining:

- _ Final Invoice and Closing Documents
- x Final Fiscal Accounting (FCTR)
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ____________

Assigned to: Electrical Engineering (School/Laboratory)

COPIES TO:

Project Director
Division Chief (EES)
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Library, Technical Reports Section
EES Information Office
Project File (OCA)
Project Code (GTRI)
Other ____________

CA-4 (1/79)

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

ELEPHONE: (404) 894-2901

May 30, 1978

Dr. Elias Schutzman
Engineering Division
1800 G Street, N.W.
National Science Foundation
Washington, D.C. 20550

Subject: Annual Technical Letter for
NSF Grant No. ENG76-81707
"High Capacity Laser Holographic Data Storage"

Dear Dr. Schutzman:

Please accept this Annual Technical Letter for the above grant. This is a brief interim report and includes reprints of our grant publications.

Progress Summary (June 1977 to June 1978)

The primary accomplishments during the last year are represented in the list of technical publications given below. These papers describe recent research results that have proven to be significant not only in volume holographic storage and processing but also in developing a much better understanding of grating devices and electro-optic crystals.

The general area of holographic optical memories has been thoroughly and extensively covered in a chapter of an edited book Handbook of Optical Holography to be published by Academic Press in 1978.

A new type of optical digital parallel processing capability using holography has been proposed. The Boolean logic operations of AND, OR, EXCLUSIVE OR, and COMPLEMENT have been shown to be possible in a single holographic cycle. All bits on one binary data page are operated on with the corresponding bits on a second page. Single-step processors using unchangeable recording materials have been shown to be useable as parallel optical comparators and correlators. Multiple-step processors using continuously-changeable recording materials produce further computing power including parallel arithmetic and parallel associative processing.

A new, general multiwave coupled-wave theory has been developed to describe grating diffraction. Grating devices are used in the deflection, guidance, coupling, distributed feedback, and modulation of light in areas of application such as integrated optics, acousto-optics, communications, signal processing, holography, holographic optical elements, spectroscopy, and information storage. This single basic theory has been shown to give accurate results for gratings of any thickness, any arbitrary periodic grating shape, and any type and level of modulation.

Electro-optic material diagnostic techniques, developed previously, have been used to establish the parameters and processes occurring in a particular electro-optic crystal sample. This information is useful in that a material specimen may be analyzed with routine measurements to determine whether it is suitable for a particular application (such as for a data recorder, modulator, grating coupler, ets.). This greatly relieves the need to fabricate an actual device in order to test it.

Extremely high quality data holograms with excellent signal-to-noise ratios have been carefully recorded for demonstration purposes. A sequence of 12 holograms has been recorded in a common volume (less than 1 mm^3) of a lithium niobate crystal using angular multiplexing. A video tape has been recorded showing the high contrast reconstructions as the reference beam is scanned through the sequence of holograms. Utilizing careful, precise procedures, absolutely no scattered light or crosstalk was observed or measured to within the detection capability of the instrumentation.

Personnel

The following personnel have been involved in one or more aspects of this grant. Many of these people were supported with State of Georgia funds. Faculty involved are: T.K. Gaylord (Principal Investigator) and W.R. Callen (Faculty Associate). Research Associates involved are: R. Magnusson and M.G. Moharam. Graduate Students involved are: C.C. Guest, H.M. Jarrett, and J.E. Weaver. Undergraduate Students involved are: P.M. Camp, S.E. Ralph, and J.L. Selikoff.

Technical Publications

Technical journal papers that have been published based on the research performed on this grant include:

1. R. Magnusson and T.K. Gaylord, "Analysis of multiwave coupled-wave diffraction of thick gratings," Journal Optical Society of America, vol. 67, pp. 1165-1170, September, 1977.

2. T.K. Gaylord, R. Magnusson, and J.E. Weaver, "Optical digital processing of two-dimensional digital data," Proceedings of the S.P.I.E., vol. 118, pp. 80-85, 1977.

3. R. Magnusson and T.K. Gaylord, "Unified description of holographic grating diffraction," Journal Optical Society of America, vol. 67, p. 1438, October 1977.

Research papers that have been accepted for publication include:

4. R. Magnusson and T.K. Gaylord, "Solutions of the thin phase grating diffraction equation," Optics Communications, vol. 21, to appear early 1978.

5. R. Magnusson and T.K. Gaylord, "Diffraction efficiencies of thin phase gratings with arbitrary grating shape," Journal Optical Society of America, vol. 68, to appear June 1978.

6. R. Magnusson and T.K. Gaylord, "Diffraction regimes of transmission gratings," Journal Optical Society of America, vol. 68, to appear June 1978.

7. T.K. Gaylord, "Digital data storage," Handbook of Optical Holography (H.J. Caulfield, editor). New York: Academic Press, 1978.

Sponsor Visits

The most recent sponsor visit was by Dr. Charles Polk, Director of the Engineering Division on August 5, 1976. He visited Georgia Tech and reviewed both the experimental and the theoretical work being performed on this grant. The next NSF sponsor visit is anticipated in August 1978.

Awards

The 1977 "Award for Outstanding Doctoral Research in Engineering" by the Georgia Tech chapter of Sigma Xi was awarded to Robert Magnusson for his thesis entitled "Dynamic Theory of Volume Holographic Recording and Readout in Electro-Optic Crystals."

The 1977 "Outstanding Young Engineer of the Year" award by the Georgia Society of Professional Engineers was presented to Thomas K. Gaylord.

The 1978 "Award for Sustained Research in Engineering" by the Georgia Tech chapter of Sigma Xi was awarded to Thomas K. Gaylord for research in the area of solid state holography.

If any further information is needed, please contact me and I will be happy to supply it to you.

Very sincerely,

Thomas K. Gaylord
Associate Professor

TKG/jdg
Enclosures: 2 copies each of
J. Optical Soc. Am. 67, 1165 (1977).
Proc. S.P.I.E. 118, 80 (1977)

AN IMPORTANT RESULT

FROM

NSF-SPONSORED RESEARCH

MULTIWAVE COUPLED-WAVE THEORY OF GRATING DIFFRACTION

developed by R. Magnusson and T. K. Gaylord

Georgia Institute of Technology

Grating devices have wide application in a variety of fields. Such devices are used in the deflection, guidance, coupling, distributed feedback, and modulation of waves. Areas of application include integrated optics, acousto-optics, communications, signal processing, holography, holographic optical elements, spectroscopy, and information storage. Due to these applications, the practical importance of gratings is rapidly increasing. Consequently, many researchers have expended considerable effort in modeling and analyzing electromagnetic wave diffraction by gratings.

Coupled-wave techniques have been used extensively to formulate numerous aspects of the grating diffraction problem. The result is a relatively simple formulation that is easily interpreted physically.

Coupled-wave theory, however, has generally been considered to be inherently approximate and thus not capable of providing exact results. Rigorous modal theory, with its great complexity and relatively abstract multiple-step calculational procedures, has provided the needed method of obtaining exact results for the amplitudes of the diffracted waves for a general grating. Now, coupled-wave theory has been extended and generalized to allow it to give fully equivalent exact results describing diffraction by spatially periodic gratings.

A new, very general multiwave coupled-wave theory of diffraction by planar gratings has been developed. This single basic approach is shown to give accurate results for gratings of any thickness ("thin", "thick", or intermediate), any arbitrary periodic grating shape (sinusoidal, square-wave, sawtooth, or other nonsinusoidal shapes), any type of modulation (refractive-index, or absorption, or mixed), any level of modulation, and any grating type (transmission or reflection). This approach is applicable for any input polarization (E-mode polarization, H-mode polarization, or other polarization), and angle of incidence (including the fundamental Bragg angle and higher-order Bragg angles), and any wavelength. Using the multiwave coupled-wave approach, diffracted amplitudes may be calculated directly using elementary numerical techniques (or using analytical expressions for important limiting cases).

Applying the multiwave coupled-wave theory, calculations have been performed showing the existence of single-wave, two-wave, and multiple-wave diffraction regimes for transmission gratings. The transitions between these regimes and their relationship to elementary "thin" and "thick" grating theories have been claculated. In each case it has been explicitly shown how general multiwave coupled-wave theory describes the limiting diffraction regimes and how it reduces to analytic results available for the numerous special cases that have been treated in the literature. Concise relationships have been derived from thin phase, absorption, and mixed gratings. New alternate analytical approaches for thin gratings are shown to evolve naturally from multiwave coupled-wave theory. Revised values of the maximum diffraction efficiencies of thin absorption gratings have been calculated and discussed in terms of previously cited values. The special case of a three-wave diffraction regime for a thin absorption grating has been studied both in terms of transmittance and absorption coefficient modulations.

A rigorous proof of the equivalence of multiwave coupled-wave theory and exact modal theory has been developed. This establishes the accuracy of the present multiwave coupled-wave theory. The detailed connection between the theories is now known. The coupled-wave approach has been discussed in relation to modal theory. The coupled-wave theory's superior ability to provide physical insight, simple formulation, and ease of calculation is obviously an enormous advantage.

This work provides a single, almost universal tool for the analysis of grating devices along with procedures on how to use it. This should be invaluable to both theoretical and experimental workers in the field of grating diffraction.

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I—PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
Georgia Institute of Technology Atlanta, Georgia	Electrical & Optical Communications	ENG76-81707
	4. Award Period From 6/1/77 To 11/30/79	5. Cumulative Award Amount $75,600

6. Project Title

"High Capacity Laser Holographic Data Storage"

PART II—SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

Optically-induced and electrically-induced refractive index changes in electro-optic crystals were investigated to determine their potential as a mechanism for high capacity data storage and high throughput information processing. The induced phase changes are periodic gratings and superpositions of gratings. These gratings form the diffractive elements and the holograms that implement the signal processing and data storage operations. The present work resulted in a broad understanding of 1) the grating formation process in electro-optic crystals and 2) the diffraction characteristics of three-dimensional volume gratings. In the grating formation area, a general analysis of the photorefractive process in electro-optic crystals with arbitrary electron migration lengths was published. This showed that long migration lengths were common in these materials though that had not previously been considered. In the area of diffraction characteristics of gratings, a new general multiwave coupled-wave analysis was developed and published. This more complete theory has for the first time allowed the calculation of accurate diffraction results for gratings of any thickness ("thin" or Raman-Nath regime, "thick" or Bragg regime, and intermediate regime). Also an accurate method for determining the diffraction regime associated with a grating (and incident wave) was developed and published. Finally, an analysis of the diffraction of nonuniform beams (such as Gaussian) was developed and published. This analysis resulted in the first analytic solutions for the complicated finite beam diffraction problem.

PART III—TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (✓)	Approx. Date
a. Abstracts of Theses	x				
b. Publication Citations			x		
c. Data on Scientific Collaborators			x		
d. Information on Inventions			x		
e. Technical Description of Project and Results		x			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Thomas K. Gaylord		06/16/80

Form Approved OMB No. 99R0013

Publications attached to NSF Form 98A (two copies each for NSF)

1. T. K. Gaylord, "Digital Data Storage," in Handbook of Optical Holography (H. J. Caulfield, editor). New York: Academic Press, 1979, pp. 379-413.

2. T. K. Gaylord, Optical Spectra, vol. 13, pp. 81-83, June 1979.

3. C. C. Guest and T. K. Gaylord, Proc. S.P.I.E., vol. 185, pp. 42-50, 1979.

4. M. G. Moharam, T. K. Gaylord, and R. Magnusson, J. Appl. Phys., vol. 50, pp. 5642-5651, September 1979.

5. M. G. Moharam, T. K. Gaylord, and R. Magnusson, Optics Comm., vol. 32, pp. 14-18, January 1980.

6. M. G. Moharam, T. K. Gaylord, and R. Magnusson, Optics Comm., vol. 32, pp. 19-23, January 1980.

7. M. G. Moharam, T. K. Gaylord, and R. Magnusson, J. Opt. Soc. Am., vol. 70, pp. 300-304, March 1980.

8. C. C. Guest and T. K. Gaylord, Appl. Optics, vol. 19, pp. 1201-1207, 1 April 1980.

9. M. G. Moharam, T. K. Gaylord, and R. Magnusson, J. Opt. Soc. Am., vol. 70, pp. 437-442, April 1980.